HEAT CONSERVATION

UDC 691.618.92

DETERMINATION OF PRACTICAL PROPERTIES OF HEAT-INSULATING FOAM GLASS

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Translated from *Steklo i Keramika*, No. 1, pp. 3 – 5, January, 2008.

The process of heat-treatment of heat-insulating foam glass is analyzed by means of mathematical modeling. The effect of the highly porous structure and radiation characteristics of the material on the technology used to manufacture the material is determined.

Energy conservation under industrial and household conditions is one of the main problems in the present economic situation because energy resources are becoming more and more expensive. A particular case of this problem is decreasing the use of heat in heat-treatment processes and for heating buildings and structures. One way to conserve heat is to use efficient heat-insulating materials. There are diverse directions for using highly porous heat-insulating materials for this purpose, and therefore the practical properties of such materials depend on their application and will vary.

The use of heat insulators at high temperatures (above 400°C) requires decreasing the radiation penetrability of materials. The highest structural strength together with the lowest thermal conductivity is required for heat-insulating components which are subjected to a load. On the other hand, even if there is essentially no load and the heat insulator is used under normal conditions, the questions of the optimal pore size in the conducting material and the ratio of the minimum cost for producing foam glass and the maximum heat-insulating properties of the manufactured product remain.

Let us examine the effect of the composition of a raw materials batch on the absorptivity of the highly porous foam glass obtained.

Analysis of the data in Fig. 1 showed that samples Nos. 6 and 8, which were manufactured using a carbon-containing foaming agent, possess the highest absorptivity, which is 1.5 and more times greater than that of samples obtained using a carbonate foaming agent (Nos. 1, 2, 5, 7, 9, and No. 3, which has a similar glass composition).

The integral radiation characteristics of a these samples of foam glass are presented in Table 1. The absorptivity of these samples increases substantially (by a factor of 2.6) when Fe_2O_3 is added (samples Nos. 1, 2, and 5). The temperature regime required to obtain the samples (overheating) has only a negligible effect on the integral absorptivity (samples Nos. 2 and 5), but it causes matter to be redistributed.

In summary, the absorptivity of foam glass depends not only on the initial composition of the glass but also on the form of the foaming agent, the character of the heat treatment, and other factors.

Let us examine the effect of the absorptivity on the thermal characteristics of foam glass. Using a mathematical model of the structure of foam glass, we shall determine the dependence of the distribution of the heat field over the cross-section of a sample of foam glass on the absorptivity with uniform cooling.

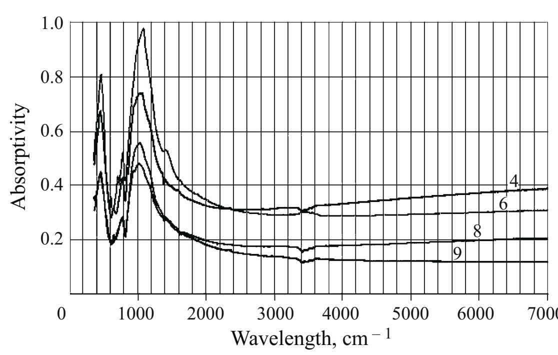

Fig. 1. IR spectrograms of the experimental samples. The numbers on the curves are the sample numbers.

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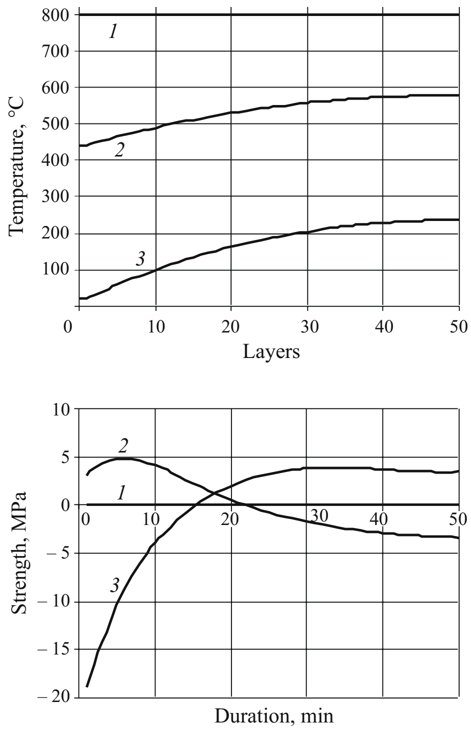

Fig. 2. Distribution of temperature and stress over the cross-section of the sample: *1*) start of heat treatment; *2*) intermediate value; *3*) end of heat treatment.

For convenience in presenting the data we shall introduce a criterion for the distribution of the heat field — the minimum-to-maximum temperature ratio of the heat field:

$$K_{\mathrm{d}} = t_{\min}/t_{\max}.$$

This criterion shows how close to a uniform state the distribution of the temperature field over the cross-section of the sample is. If the temperature values of the temperature field are the same, then this criterion will be 1 and the temperature gradient between layers will be 0 (Fig. 2). Such a distribution of the temperatures of the layers will correspond to the lowest stress–strain state generated in the system by heat.

TABLE 1.

Sample No.	Foaming agent	Absorptivity	Transmissivity
1	Chalk	0.55	0.35
2	″	0.21	0.69
3	″	0.45	0.45
4*	No data	0.40	0.50
5	Chalk	0.21	0.69
6	Carbon + soot	0.70	0.20
7	Chalk	0.45	0.45
8	Soot	0.60	0.30
9	Chalk	0.30	0.60

* Sample provided by the Foamglass Company.

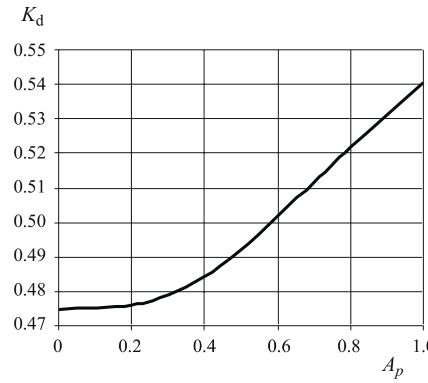

Fig. 3. The absorptivity versus the temperature distribution over the cross-section of a sample.

This situation is ideal for heat-treating glass-based parts (for glass with infinite thermal conductivity):

$$\lambda \to \infty\colon \mathrm{d}Q = \frac{\mathrm{d}T}{\mathrm{d}n}\,\mathrm{d}S\,\mathrm{d}\tau;$$

$$\lim_{\lambda\to\infty} \mathrm{d}T = \lim_{\lambda\to\infty} \frac{\mathrm{d}Q\mathrm{d}n}{\lambda \mathrm{d}S\,\mathrm{d}\tau} = 0,$$

where λ is the thermal conductivity, Q is the heat flux, n is the thickness, S is the area, and τ is the time.

However, the heat-insulation properties of a material are characterized by the heat resistance — the reciprocal of the thermal conductivity. In this connection, ideally, the criterion K_{d} for heat-insulating materials should go to zero.

The dependence of the distribution K_{d} of the temperature field over the cross-section of a sample on the regime absorptivity A_{r} at the end of heat treatment is displayed in Fig. 3. As the absorptivity of the foam-glass matrix increases, the temperature field becomes more evenly distributed over the cross-section of the sample. Evidently, this is because, as the absorptivity increases, the radiation component plays an increasingly larger role in the resulting heat flux as compared with other methods of heat transfer, since the layers of the foam glass absorbs more thermal radiation. However, it is evident on the basis of the data in Fig. 4 that the effective thermal conductivity λ_{eff} of the material increases substantially, and therefore the heat-insulating properties of the foam glass degrade at high operating temperatures (above 400°C). However, at temperatures of the order of 20°C the radiative heat flux actually has no effect on the overall thermal conductivity of the material.

On the other hand, as the absorptivity of the material decreases (Fig. 5), the residual stresses increase. This makes the heat-treatment regime more severe and substantially increases energy consumption.

In summary, the absorptivity of layers of foam glass must be regulated by taking account of the future application of the glass and by optimizing the manufacturing process.

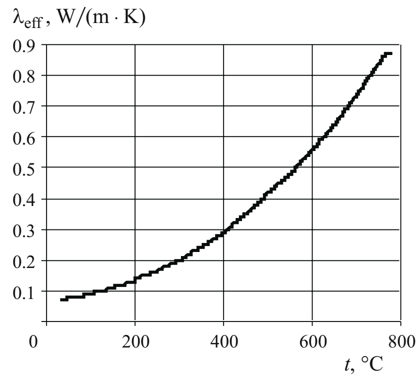

Fig. 4. Effective thermal conductivity versus temperature.

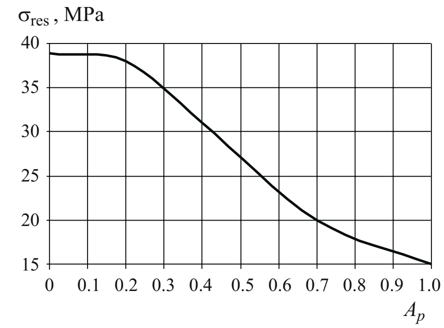

Fig. 5. Effect of the absorptivity of foam glass on residual stresses.

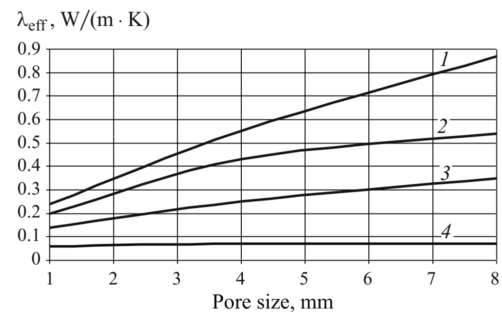

Fig. 6. Thermal conductivity of foam glass versus pore size at temperatures 800 (*1*), 650 (*2*), 450 (*3*), and 20°C (*4*).

When foam glass is used at temperatures only slightly above normal values (up to 200°C), efforts must be made to obtain a foam glass with the highest possible absorptivity, making it possible to produce more uniform temperatures over the cross-section of articles.

This approach will make it possible to obtain more uniformly distributed pores and to decrease the thermal deformation of an article (residual and temporary stresses) and energy consumption for foaming and annealing the foam glass.

The pore size, porosity, and density are the main parameters affecting the heat insulation properties of foam glass and, correspondingly, determining its operational characteristics as a heat insulator. However, if it is known that increasing the porosity and decreasing the density improve the heat insulation properties (decrease the effective thermal conductivity), then the effect of pore diameter on them requires additional study.

As the pores in a sample increase in size, the radiation component of the heat flux increases somewhat and therefore the effective thermal conductivity of the foam glass at high temperatures increases. This effect will have a positive influence on the foam-glass manufacturing technology, promoting a decrease of residual stresses and therefore lower energy consumption for production (annealing). However, on the other hand, it is believed that as pore size decreases, the strength of the finished articles increases [1], i.e., the ultimate strength and, correspondingly, the admissible stresses which the foam-glass sample can withstand without collapsing, increases. This makes it possible to decrease the annealing time of the foam glass at temperatures below 480°C.

In summary, the answer to the question of the most effective pore size for a manufacturing operation is not unique and requires a more detailed analysis.

Figure 6 displays the results of modeling of the thermal conductivity of foam glass with pore sizes ranging from 1 to 8 mm and density 200 kg/m^3 depending on the temperature. The plots reflect the pore-size dependence of the thermal conductivity of the foam glass for the temperatures of interest to us: the average temperature at which the foam glass is used for exterior facing of buildings — 20°C, maximum temperature at which the foam glass is used — 450°C, annealing start temperature — 650°C, and maximum foaming temperature — 800°C.

An increase of pore size at low temperatures actually has no effect on the thermal conductivity of foam glass (a difference of a factor of 1.16), and the pore size must be decreased to the maximum extent possible in order to increase the strength of an article. However, at the highest operating temperature of foam glass an increase of pore size from 1 to 8 mm increases the thermal conductivity by a factor of 2.3, and therefore reducing the pore size to a minimum improves the heat insulating properties of the article. At the highest manufacturing process temperatures an increase of the pore size results in an increase of the thermal conductivity of foam glass by a factor of 2.7 with annealing and by a factor of 3.6 with foaming, lowering the energy consumption for heat treatment.

In summary, in order to manufacture of foam glass effectively it is necessary to take into account the subsequent use and optimal structure of the heat-insulating material obtained. However, this requires using an effective system for controlling production with the maximum possible automation of the process of changing over to a new form of production.

REFERENCES

1. *Handbook of Radiative Heat Transfer in High-Temperature Gases* [in Russian], Énergoatomizdat, Moscow (1984).